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Testing of Indoor Radon Reduction Techniques in Eastern Pennsylvania An Update

American ATCON, Inc., Wilmington, DE

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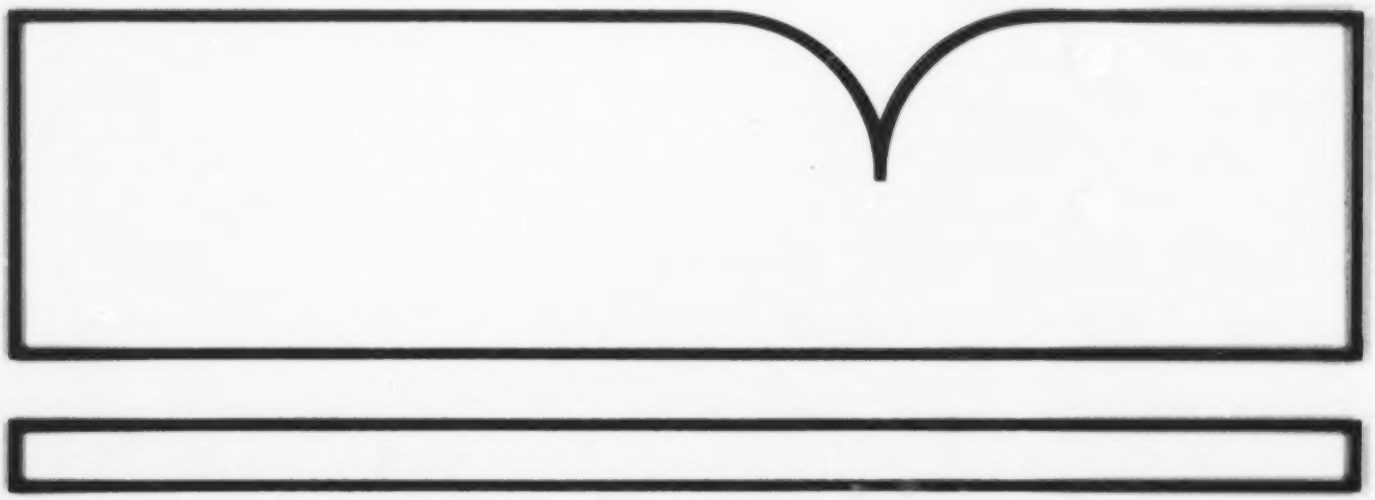

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TESTING OF INDOOR RADON REDUCTION TECHNIQUES IN EASTERN PENNSYLVANIA: AN UPDATE

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16. ABSTRACT The paper updates information from EPA tests of indoor radon reduction techniques on 38 houses in the Reading Prong area of eastern Pennsylvania. All were basement houses with hollow-block or poured-concrete foundation walls. The reduction approaches tested in most houses involved active soil ventilation, including: suction on the footing drain tile system; suction under the concrete slabs, using pipes inserted through the slabs from inside the houses; and ventilation of the void network inside hollow-block foundation walls. Heat recovery ventilators (HRVs) were tested in three houses. Current results confirm that, for the houses tested, drain tile suction appears consistently able to provide high radon reductions when a complete loop of drain tile exists, often reducing high-radon-level houses to 4 pCi/l (148 Bq/cu m) and less. Sub-slab suction (with pipes through the slab) can also provide high reductions if enough suction pipes are located properly. Placing one or more sub-slab suction pipes near each perimeter wall appears to aid in treating the major soil gas entry routes, although fewer pipes can sometimes give high reductions if conditions are favorable. Ventilation of block wall voids can be effective if major wall openings can be adequately closed, and if there are no major slab-related entry routes remote from the walls.

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EPA has installed radon reduction measures in 38 houses in the Reading Prong region of eastern Pennsylvania. All were basement houses with hollow block or poured concrete foundation walls. The reduction approaches tested in most houses involved active soil ventilation, including: suction on the footing drain tile system; suction underneath the concrete slabs, using pipes inserted through the slabs from inside the house; and ventilation of the void network inside hollow block foundation walls. Heat recovery ventilators (HRVs) were tested in three houses.

The current results confirm that, for the houses tested here, drain tile suction appears consistently able to provide high radon reductions when a complete loop of drain tile exists, often reducing high-radon houses to 4 pCi/l (148 Bq/m^3) and less. Sub-slab suction (with pipes through the slab) can also provide high reductions if a sufficient number of suction pipes are located properly. Placement of one or more sub-slab suction pipes near each perimeter wall appears in this testing to aid in treating the major soil gas entry routes, although fewer pipes can sometimes give high reductions if conditions are favorable. Ventilation of block wall voids can be effective if major wall openings can be adequately closed, and if there are no major slab-related entry routes remote from the walls; however, a well-designed sub-slab suction system might give high reductions more consistently. For effective radon reduction using any active soil ventilation technique, it is important that major wall and slab openings be closed, and that a fan be employed that is capable of developing adequate static pressure. HRVs appear capable of giving moderate radon reductions with reasonably sized units in houses having typical natural infiltration rates. While dilution appears to be a predominant mechanism in determining HRV performance, other mechanisms also play a role, so that reduction throughout a house cannot always be reliably predicted based solely on dilution considerations.

TESTING OF INDOOR RADON REDUCTION TECHNIQUES IN EASTERN PENNSYLVANIA: AN UPDATE

Introduction

As part of the U.S. Environmental Protection Agency (EPA) program to develop and demonstrate cost-effective methods for reducing concentrations of radon inside houses, EPA has been sponsoring a project with AMERICAN ATCON to test developmental radon reduction measures in existing houses in the Reading Prong region of eastern Pennsylvania. The initial results from this project were described in an earlier paper (1), which discussed the first 18 houses that had been tested since the project began in the Spring of 1985. This project has now involved testing in 38 existing houses, including significant improvements to the mitigation installations in some of the houses from among the original 18.

The 38 houses were selected to be representative of the substructure types common in that region. All of the houses have basements with concrete floor slabs, sometimes with an adjoining slab-on-grade or crawl-space wing. The foundation walls are constructed of hollow block, or of poured concrete. The houses had initial indoor radon concentrations of at least 20 picocuries per liter (pCi/l)--or 740 becquerels per cubic meter (Bq/m^3) --as determined by prior measurements conducted by the Pennsylvania Department of Environmental Resources. One house had an initial level of 1,200 pCi/l (44,000 Bq/m^3). In all but one house, soil gas is the predominant source of the radon in the house. Well water is the predominant source in the remaining house (with up to 310,000 pCi/l, or 11.5 MBq/m^3, in the water), and is an important secondary contributor in a number of the other houses, with airborne radon levels in the basement temporarily swelling by 60 pCi/l (2,220 Bq/m^3) or more in worst-case houses when the clothes washer is operated. Extensive gamma measurements in and around the houses gave no suggestion that building materials are an important contributor in any of the houses.

Active soil ventilation approaches for radon reduction were selected for testing in 34 of the houses. Where soil gas is the predominant source, these approaches appear to offer the potential for achieving, at moderate cost, the very high levels of reduction needed to reach the EPA guideline of 4 pCi/l (148 Bq/m^3) in some of these houses (sometimes over 99 percent). HRVs are being tested in three of the houses, where the initial radon level is less severely elevated (generally where reductions no greater than 75 percent are required). Greater reductions with ventilators were not considered practical in view of the natural infiltration rates in these houses. Well water treatment systems are being tested in two houses, including one where an active soil ventilation technique is also under test.

The methods that are being investigated for achieving active soil ventilation have been described previously (1,2). These approaches involve the use of one or more fans to draw suction on (or to blow outdoor air into) the soil around the foundation of the house in an effort to divert the soil gas. If the soil ventilation system is operated in suction, it will be effective only if it is able to maintain soil gas pressure near all major soil gas entry routes at a level lower than that inside the house. If the system is operated to blow air into the soil, it must maintain air pressure sufficiently high near the entry routes so that the soil gas will be forced away. The major entry routes generally include any openings through the slab and walls; with hollow block foundation walls, the void network inside the walls can also serve as a conduit for the soil gas into the house. To

achieve adequate treatment of all of these entry routes, the soil ventilation system requires a suitable combination of: a) ventilation points located sufficiently close to the entry routes; b) reasonable permeability (e.g., in the soil and crushed rock underneath the slab) so that entry routes remote from the ventilation points are treated; c) fans capable of developing an adequate static pressure at the soil gas (or air) flows encountered in the system piping, so that suction (or pressure) will be distributed remote from the ventilation points; and d) closure of major openings in the slab and walls, so that fan suction (or pressure) is not lost through the leakage of house air into the suction system (or of fan air into the house) through these openings.

In most of the active soil ventilation installations reported here, the fans used have been units capable of moving 270 cfm (127 l/sec) at zero static pressure, and capable of developing over 1.0 in. of water (250 Pa) static pressure before stalling.

Measurement Methods

Radon gas is measured using a Pylon Model AB-5 semi-continuous radon monitor, equipped with a 17.4 $in.^3$ (285 ml) Lucas scintillation cell. The Pylons are programmed to measure radon hourly, and are generally operated in each house for at least 48 hours (and sometimes as long as 96 hours) both before and after the radon reduction technique is activated. Measurements are normally made in the basement of the house with all basement doors and windows closed. Sometimes measurements are also made upstairs. Wherever possible (and in almost all cases for post-mitigation measurements), the Pylon data reported here are those that have been taken during the cold-weather months in Pennsylvania (November through March), when radon levels would be expected to be highest.

Three-month integrated measurements during winter months using alpha-track detectors are made in all houses following completion of the mitigation installation.

Diagnostic testing is also conducted as warranted, including flow, pressure, and radon measurements in individual ventilation pipes, smoke tracer flow visualization, and other diagnostic tests.

Results

Drain tile suction

If drain tiles are present around the outside or the inside of the perimeter footings for water drainage purposes, these tiles are ideally located to permit suction to be drawn near some of the major soil gas entry routes; i.e., the joint between the slab and the foundation wall, and the footing region where soil gas can enter the void network inside block walls. In addition, suction drawn on the tiles might extend underneath the entire slab. The design of a drain tile suction system will depend upon whether the tiles drain to an external dry well or above-grade discharge, or to an internal sump (1,2).

The most recent results with drain tile suction are presented elsewhere (3). These recent results confirm the initial results (1), that high degrees of radon reduction appear possible -- often to 4 pCi/l (148 Bq/m^3)

and less -- when a complete loop of drain tiles surrounds the house. Of the five houses involving drain tile suction on complete loops, the two that had excursions above 4 pCi/l (148 Bq/m^3) after mitigation had interior load-bearing block structures penetrating the slab, thus providing a potential major soil gas entry route remote from the perimeter drain tiles. When the drain tiles do not form a complete loop, performance is reduced, probably because some segment of the footings and sub-slab is not receiving adequate suction. However, even with only a partial loop, significant reductions can sometimes still be achieved (84 and 96 percent in two of the six partial-loop houses tested), depending upon the extent and location of the tiles, the permeability under the slab, and the performance of the fan.

Sub-slab suction via pipes through slab

Another approach for drawing suction on the soil underneath the slab is to drill holes through the slab at appropriate locations inside the house, and to insert pipes into the crushed rock or the soil under the slab (1,2). Suction is then drawn on these pipes, and the collected soil gas is vented outdoors.

The most recent results with this sub-slab approach, for basement houses with block foundation walls and with no adjoining slab on grade, are presented elsewhere (3). These recent results suggest that the sub-slab suction results reported earlier (1) for this type of house underestimate the potential of this mitigation approach, because factors a) through d) listed in the fourth paragraph of the Introduction were not favorable. In the earlier results, the one or two centrally located suction points were perhaps too limited in number and too remote from some of the major entry routes for block houses (the wall/floor joint and the footing region); the sub-slab permeability was extremely poor in two of the houses; the fans used did not draw sufficient suction; and slab and wall openings were generally not closed. Smoke tracer testing ultimately confirmed that suction was not extending under the total slab in any of the initial four houses with sub-slab systems. These shortcomings in the earlier installations arose in part because the initial objective was to demonstrate designs that homeowners could install at minimum cost, and the increased costs and complexity associated with more suction points, larger fans, and more extensive closure of openings were omitted initially to determine whether in fact they are really necessary.

The recent sub-slab suction installations have generally utilized between three and seven suction points distributed near the perimeter block foundation walls (i.e., within about 1 ft, or 0.3 m, of the wall/floor joint), and near any interior load-bearing block walls. The objective of positioning the points in this manner is to ensure distribution of the suction underneath the entire slab (and, in particular, to prevent soil gas movement up into the void network inside the block walls, and up through the wall/floor joint). More powerful fans are now being used, and reasonably accessible slab and wall openings are closed. Recent installations testing this more extensive design in seven houses (3) reduced five of the houses to average levels below 4 pCi/l (148 Bq/m^3), and achieved reductions of 92 and 95 percent in the other two (both of which have one wall without a suction point nearby, and one of which does not yet have a high-suction fan).

Recent testing of more limited sub-slab systems (involving only one or two suction points) in other block houses has shown that the performance of the more limited systems is less predictable than that of the more extensive systems, but that significant reductions can sometimes still be achieved.

In one house having only one suction point, near one end wall in a 1000 ft^2 (93 m^2) basement, a radon reduction of 98 percent was achieved using a high-suction fan (3). In House 38, with a high-suction fan maintaining 0.95-1.4 in. of water (240-350 Pa) at the suction points, two suction points (near perimeter walls) achieved 99 percent reduction in a 1240 ft^2 (115 m^2) basement. Thus, even a limited number of suction points can sometimes give good performance if factors b), c), and d) in the Introduction are sufficiently favorable. The ability to achieve high reductions with a limited number of points is particularly important with finished basements, where it is not conveninent to place suction pipes near every wall.

Table I presents the Pylon results from testing this sub-slab suction approach in basement houses with poured concrete foundation walls, with no adjoining slab on grade. The table shows the range observed in the hourly Pylon measurements (excluding any transient periods after the fan was initially turned on, when windows were opened, etc.); the table also shows the arithmetic mean of the hourly readings.

Poured concrete walls do not contain a wall void network which the sub-slab system must prevent soil gas from entering. In addition, the absence of porous blocks and of block voids eliminates a pathway for house air to move down through the walls and into the sub-slab suction system, thus enabling the system to more effectively maintain suction under the slab. Accordingly, it might be anticipated that, with poured concrete walls, good radon reductions might be achieved with a smaller number of suction points, and with location of the points close to all of the foundation walls being less important. As shown in Table I, radon reductions greater than 90 percent were achieved in all five houses, including one (House 33) where only one suction point was utilized, and a second (House 24) with only three points in a large house (having a 1460 ft^2, or 135 m^2, basement) including a block fireplace structure which could serve as a soil gas conduit. As expected, the suctions which could be maintained in the pipes (measured at a point near where the pipe penetrates the slab) were generally slightly higher in the poured concrete houses (averaging over 1 in. of water, or over 250 Pa), relative to the block houses (which average less than 1 in. of water with the high-suction fans). High suction in the pipes near their penetration through the slab increases the likelihood that adequate suction will exist under the slab remote from the points. Only in House 34, where part of a French drain could not be closed, was house air leakage into the system sufficient to reduce suction significantly below 1 in. of water. However, a comparison of the data in Table I with those in Reference 3 for block houses having comparable high-suction fans, does not indicate that houses with poured concrete foundation walls are consistently a distinctly simpler case than are houses with block walls. Generally, comparable radon reductions seem to be achieved with a given number of suction points and with comparable fans in either type of house. Perhaps if the sub-slab treatment is sufficient to prevent soil gas from entering through the wall/floor joint and through other slab cracks -- which is necessary for houses with poured concrete walls -- then this treatment might also be sufficient to prevent soil gas from entering the void network in houses with block walls.

Table II presents the Pylon results with sub-slab suction in basement houses with poured concrete foundation walls, with an adjoining slab on grade. Two sets of houses are shown in the table: those where the system included sub-slab suction in the basement only; and those where the system also included suction under the adjoining slab-on-grade wing, by insertion of two pipes horizontally through the basement stub wall beneath the adjoining slab. As shown, treatment of the basement alone gave significant

reductions, suggesting that the basement is the major source and/or that treatment of the basement extends to the adjoining slab. For House 22, radon levels upstairs were higher than in the basement after the basement-only system was activated, which might be suggesting that the adjoining slab might be a more important residual source than the basement. But for House 23, the basement levels are still higher than upstairs, so that the basement could be the more important residual source. House 37 appears to have been reduced to acceptable levels without any direct treatment of the adjoining slab.

Treatment of the adjoining slab as well as the basement in House 22 (now House 22A in Table II) did not appear to significantly change the basement radon levels; considering the observed daily variations in radon concentrations in any given house, the post-mitigation mean basement radon levels of 7 pCi/l (260 Bq/m^3) in House 22 and 9 pCi/l (330 Bq/m^3) in House 22A are considered comparable. However, treatment of the adjoining slab reduced upstairs levels from 10 pCi/l (370 Bq/m^3) to 3 pCi/l (110 Bq/m^3), suggesting that the basement might now be the most important residual source.

Wall void ventilation

In basement houses with block foundation walls and with an integral slab, ventilation of the wall void network might achieve effective treatment when the wall voids and the wall/floor joint are the predominant soil gas entry routes. Slab cracks remote from the walls might not be adequately treated. A potential problem with wall void ventilation is that the numerous small and often-concealed wall openings are very difficult to close adequately; substantial house air and outdoor air will invariably leak into the system if it is in suction (or fan air will leak out if in pressure), so that maintenance of sufficient suction/pressure throughout the entire wall can be difficult. House air leakage into a wall suction system can sometimes be sufficiently significant to cause back-drafting of stoves and fireplaces, requiring operation of the system in pressure instead. The "individual pipe" and the "baseboard duct" approaches for wall void ventilation have been described elsewhere (1,2).

Table III presents the recent results with ventilation of the wall void network. Some of the houses in this table are those reported previously (1); in most of these cases, those initial wall ventilation installations have now been improved through more complete closure of wall openings, additional ventilation points, larger-diameter piping, or additional fan capacity. As shown, radon reductions above 90 percent were ultimately achieved in all but three of the eleven houses, although levels still average above 4 pCi/l (148 Bq/m^3) in seven of the houses. The houses in Table III represent a range of the complexities described in Reference 1 that can reduce wall ventilation performance, including inaccessible open top voids, exterior brick veneer, and block fireplace structures. In most cases, the amount of wall closure was kept within practical limits (closing accessible openings with mortar, foam, or caulk, and caulking the interior face of the sill plate to the top course of block when the uncapped top voids were covered by the sill plate). Closure efforts in House 1B were quite extensive (including, among other things, injection of foam to close the gap between the exterior brick veneer and the interior sheathing, and coating the entire face of the highly porous cinder block with waterproofing paint). Houses 8 and 14A, two of the more successful houses, were among the easiest for closure of wall openings, since all major openings (including the voids in the top blocks) were readily accessible.

Where effective closure of wall openings was possible, and where the slab did not contain major cracks or other entry routes--i.e., in Houses 5A, 8, and 14A--high radon reductions were achieved without much difficulty. In most of the other houses, where wall closure could not be completed so effectively, the system required a greater closure effort, a larger number of ventilation points, and/or more fan capacity--and sometimes performance was reduced. In House 19, where effective wall closure was possible but where the slab was badly cracked, reductions were limited--confirming that wall suction cannot always be relied upon to treat slab-related entry routes remote from the walls, regardless of how well the walls seem to be closed. The baseboard duct approach might appear to give more consistent high reductions than the individual pipe approach when the entire perimeter joint (and the joints associated with interior load-bearing block walls) can be effectively covered by the duct; however, such comprehensive installation can sometimes require a great deal of effort. Even when the block walls can apparently be effectively closed, there is such an air flow into (or out of) the walls that system pressures are almost always below 0.1 in. of water (25 Pa) near the point where the pipe enters the wall (or inside the baseboard duct)--only one-tenth that maintained in sub-slab systems.

The results with sub-slab suction in houses with block foundation walls suggest that a well-designed sub-slab system can often effectively prevent soil gas from entering the wall void network, if sub-slab permeability is adequate. However, the wall ventilation results (especially from House 19) suggest that a well-designed wall ventilation system might not so often be expected to prevent soil gas entry through remote slab cracks. Accordingly, a logical approach in high-radon block basement houses in many cases would appear to be to install sub-slab suction initially, and to possibly augment the sub-slab system with wall ventilation only if the sub-slab system proved unable to treat the walls.

Sub-slab plus wall suction

If a sub-slab suction system does not initially achieve adequate performance in a block basement house, alternative follow-up steps can be considered. These include: the installation of additional sub-slab suction points; and the addition of wall void suction points. The alternative that will provide the greatest radon reduction will depend on the particular house, and will be suggested by the results from diagnostic testing.

To determine if direct treatment of the block walls might typically produce obvious benefits in combination with sub-slab suction, available results have been compared from houses where sub-slab suction has been tested by itself, and where the same sub-slab system has been tested in combination with individual wall suction pipes. Table IV presents this comparison. For all houses, a single fan provided the suction for the entire system. In House 3/3A, the initial one-point sub-slab system was probably not optimally designed. The dramatic radon reduction achieved by the addition of five wall suction points (in a house clearly amenable to wall ventilation) might also have been achieved had five sub-slab suction points been added near the perimeter walls. Thus one cannot conclude from this house whether additional sub-slab points, or the wall points, would have been the more effective. House 7C/7D demonstrates that the addition of wall suction points can sometimes actually reduce the radon reduction performance. In this house, the large air flows entering the system through the wall suction pipes (despite dampering of the wall pipes) reduced the suction in the entire system. The reduction of suction in the sub-slab pipes (falling from as high as 1 in. of water, or 250 Pa, in the sub-slab-only system, to about 0.15 in., or 37 Pa, with the wall pipes) apparently

more than offsets any benefits from the wall treatment. Radon measurements inside the wall cavities in the sub-slab-only case (7D) gave values averaging 9 pCi/l (340 Bq/m^3), compared to up to 2,400 pCi/l (89,000 Bq/m^3) in the soil gas in the sub-slab pipes--suggesting that the sub-slab system is doing a fairly good job of preventing soil gas from entering the void network. The results from House 20B/20C are not yet complete; however, the results with the combined sub-slab-plus-wall system appear so good, that the issue in this house would seem to be whether sub-slab suction by itself can do as well.

Diagnostic results from given houses might sometimes reveal occasions where block-wall-related entry routes will not be adequately treated by sub-slab suction alone. In these houses, addition of wall ventilation points will be necessary. But based upon results from House 7C/7D, it might be expected that, in a number of cases, the addition of wall pipes to a sub-slab system might not provide a dramatic improvement. In these cases, if an initial sub-slab installation does not provide sufficient reductions, the addition of sub-slab points might give results equal to--if not superior to--the addition of wall points. If wall void ventilation is employed in conjunction with sub-slab suction, it might be desirable to use a separate fan and piping system for the wall ventilation, so that the wall air flows do not reduce the suction in the sub-slab pipes.

Heat Recovery Ventilators

The results obtained with HRVs are summarized in Table V. In each of the three block basement houses, a single nominal 200 cfm (94 l/sec) ventilator was installed, and the inlet and outlet flows balanced, by a local vendor. In all houses, the stale house air was exhausted entirely from the basement; the fresh incoming air was sometimes supplied entirely upstairs (i.e., on the "first floor"), and sometimes entirely into the basement.

Most of the results in Table V seem to be suggesting that mechanisms other than simple dilution are playing a role in the performance of the HRVs, if in fact the natural infiltration rates in these houses are around 0.5 air changes per hour. (The results of perfluorocarbon ventilation rate testing are not yet available.) The 70 to 80 percent upstairs reductions when the fresh air is supplied upstairs in Houses 17A and 18A are above the 65 to 70 percent maximum reductions that would be predicted based upon dilution in the upstairs alone. Possibly, the upstairs in these houses might be being slightly pressurized relative to the basement by the upstairs delivery, reducing the flow of relatively high-radon basement air upstairs and thus augmenting the dilution effects. The low reductions in the basements of these two houses during upstairs delivery (including an increase in basement radon levels in one case in House 17A) could reflect the limited increase in ventilation that the basements see during upstairs delivery, and/or an increase in soil gas influx into the basement due to the localized depressurization effects of the HRV exhaust fans. (The stratification in radon levels between upstairs and downstairs can exist because both houses employ hot water space heating, and thus avoid the communication that a central forced-air heating system would create.) This preferential treatment of the upstairs at the expense of the basement can be desirable when the upstairs is the primary living area.

The 37 to 45 percent reduction achieved in the basements of all three houses when the fresh air is supplied entirely to the basements, are all well below the maximum reductions of 55 to 75 percent that would be calculated based upon dilution effects in the basement alone. For House 17A, the reduced basement reductions apparently resulted because some of the fresh air circulated upstairs (not surprising, since the door between the

basement and upstairs was open); the House 17A basement delivery case is the only case in Table V where the combined upstairs and downstairs reductions are consistent with a dilution-only mechanism. However, in Houses 18A and 28A with basement delivery, the upstairs reductions are not sufficient to account for the low basement reductions through fresh air circulation upstairs; in these cases, localized depressurization caused by the HRV might have been increasing soil gas influx, partially offsetting the dilution effects. The upstairs reductions in House 28A are significantly less than the basement reductions, which suggests that soil gas has a direct route upstairs without first being mixed (and reduced) in the basement air. A block fireplace/chimney structure in one wall of this house is one possible such direct avenue, not treatable using a basement-only HRV configuration.

Conclusions

1. If significant (90+ percent) radon reductions are needed, drain tile suction should be one of the first approaches considered when a complete drain tile loop exists (or sometimes perhaps even if only a partial loop exists), because drain tile suction is often very effective, relatively inexpensive, and potentially less obtrusive than other active soil ventilation approaches.

2. If drain tile suction is not an option, sub-slab suction (using individual pipes through the slab and/or foundation walls) should be the next approach considered, because this approach appears consistently able to provide high reductions if designed to develop effective suction near all major soil gas entry routes. One way to help ensure that effective suction is established under the slab (especially in houses with block foundation walls) appears to be to place one or more suction points near each load-bearing wall, and perhaps near other suspected entry routes. Such extensive placement of suction points might not always be necessary. The actual number and location of the required suction points will be determined by the permeability under the slab, among other factors.

3. In houses with block foundation walls, ventilation of the void network inside the walls can give high degrees of radon reduction, if major wall openings can be adequately closed and if there are no major slab-related soil gas entry routes remote from the walls. Current results suggest that a well-designed sub-slab suction system by itself might be expected to effectively treat both slab- and wall-related entry routes more often than might a wall ventilation system alone; accordingly, in many block basement houses needing high reductions, it might be advisable to initially consider sub-slab suction rather than wall ventilation. Wall ventilation might sometimes be required in combination with sub-slab suction to reduce high-radon block houses below 4 pCi/l.

4. As expected, dilution appears to be a major mechanism in determining the performance of heat recovery ventilators. However, other mechanisms (such as changes in soil gas influx) can also play a role, so that the radon reduction performance of a ventilator on different floors of a given house cannot always be reliably predicted a priori based solely on dilution considerations. Moderate reductions (up to 80 percent in some parts of the house under some circumstances) can be achieved with a reasonably sized HRV in houses having typical natural infiltration rates, sometimes at the expense of lesser reductions in other parts of the house. One issue in selecting a HRV is whether it will be cost-effective relative to a comparable increase in natural ventilation without heat recovery.

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Table I. Results with sub-slab suction using pipes through slab (basement houses with poured concrete foundation walls, with no adjoining slab on grade)

House No.	Rn Levels-System Off (pCi/l) Range	Arith. Mean	Rn Levels-System On (pCi/l) Range	Arith. Mean	Percent Reduction In Mean	Comments
24	24-65*	44*	2-5	3	93	3 suction points beside perimeter walls (2 near one end wall, 1 near the other end wall, due to existing/planned wall/floor finish). 490 ft^2 of slab area per point. 1.1-1.3 in. WC suction in each pipe near the slab. Wall/floor joint, cold joint caulked. Part of one concrete wall interrupted by block fireplace structure.
25	12-310*	148*	5-16	9	94	4 suction points around perimeter (270 ft^2 per point). 0.7-0.95 in. WC suction in each pipe. Performance might be being reduced by condensate plugging temporary hose connecting fan to piping.
33	69-97	84	3-7	5	94	1 suction point in one corner (620 ft^2 per point). 1.4 in. WC suction.
34	549-810	696	3-7	5	99	6 suction points around perimeter walls (210 ft^2 per point). 0.60 - 0.72 in. WC suction in each pipe. Most of French drain around perimeter mortared closed.
35	87-298	164	0.5-2	1	99	4 suction points (3 around perimeter exterior walls of basement living area, 1 by stud wall between living area and adjoining garage). 240 ft^2 per point. 1.0-1.1 in. WC suction. No pipes in garage half of basement slab.

*All measurements were obtained during cold-weather months (November through March) except those marked with an asterisk.

Conversion factors: becquerels per cubic meter = 37 x value in picocuries per liter
square meters = 0.093 x value in square feet. Pascals = 248 x value in inches of water

Note: In these and subsequent tables, the reported radon concentrations are rounded to the nearest whole pCi/l. Reported percentage reductions are based upon the non-rounded values, and thus might sometimes appear slightly high or low.

Table II. Results with sub-slab suction using pipes through slab (basement houses with poured concrete foundation walls, with adjoining slab on grade)

House No.	Basement Rn Levels-System Off (pCi/l) Range	Arith. Mean	Basement Rn Levels-System On (pCi/l) Range	Arith. Mean	Percent Reduction In Mean	Comments
Houses where only the basement is treated						
22	22-54*	34*	3-15	7	77	4 suction points around perimeter of basement but no point near front wall (110 ft^2 of basement slab area per point). 0.5 in. WC suction in each pipe. Levels upstairs average 10 pCi/l (higher than basement) during operation, suggesting that untreated 440 ft^2 slab on grade is a source. Peformance possibly reduced by moisture condensation in temporary hose. Levels in basement as high as 19 pCi/l when clotheswasher in use during mitigation.
23	87-103	95	4-12	8	92	4 suction points around perimeter of basement (230 ft^2 of basement slab area per point). Suction also drawn on enclosure constructed in basement over the joint between the basement stub wall and the slab of the ajoining 680 ft^2 slab on grade. 1.0 in. WC in each of the sub-slab suction pipes, 0.05 in. WC in pipes sucking on enclosure. Average levels up-stairs 5 pCi/l (lower than in basement) during operation, suggesting that basement is still a larger source than is adjoining slab.
37	10-33	19	0.5-2	1	97	6 suction points around perimeter of basement (150 ft^2 of basement slab per point). 0.42 - 0.5 in. WC suction. Adjoining slab on grade is 390 ft^2.
Houses where both the basement and the adjoining slab are treated						
22A	22-54*	34*	5-16	9	74	4 suction points around perimeter of basement (House 22 above) plus 2 suction points under slab on grade (SOG) via pipes through basement stub wall under adjoining slab (110 ft^2 of basement per basement point, 220 ft^2 of SOG per SOG point). 0.80 - 0.85 in. WC suction on each point. Upstairs levels averaged 3 pCi/l during mitigation, suggesting that basement might be major remaining source.
36	66-171	142	1-4	2	99	5 suction points around perimeter of basement (160 ft^2 of basement per basement point) plus two suction points under SOG via pipes through stub wall in basement (300 ft^2 of SOG per SOG point). 0.45-0.55 in. WC suction. One of basement suction points is a sump pit, might be providing suction on drain tiles of uncertain extent.

*All measurements were obtained during cold-weather months (November through March) except those marked with an asterisk.

Table III. Results with block wall ventilation (basement houses with hollow-block foundation walls, with no adjoining slab on grade)

House No.	Rn Levels-System Off (pCi/l) Range	Rn Levels-System Off (pCi/l) Arith. Mean	Rn Levels-System On (pCi/l) Range	Rn Levels-System On (pCi/l) Arith. Mean	Percent Reduction In Mean	Comments
Individual suction points in walls						
5A	67-200	115	3-8	5	96	6 vent points evenly distributed around perimeter walls. One fan blowing into walls. 0.05 - 0.07 in. WC static pressure in pipes near wall entry. Top wall voids, wall cracks effectively closed; floor drain treated.
6	33-68*	50*	21-33*	27*	46	4 vent points, one in each perimeter wall. Two fans blowing into walls. Top voids, other wall opening inaccessible, not effectively closed. Exterior brick veneer on all walls, fireplace on one wall. System ultimately replaced by sub-slab suction.
7A	156-626	402	14-67	32	92	7 vent points (six in perimeter walls, one in interior load-bearing wall). Two fans in suction. 0.02-0.03 in. WC suction. Some top wall voids not amenable to effective closure. Slab openings closed. Brick veneer on all walls. System expanded to include combined wall plus sub-slab vent (House 7C/7D in Table IV).
8	53-159*	100*	2-4	3	97	4 vent points, one in each perimeter wall. One fan in suction. 0.02-0.07 in. WC suction. Most of top wall voids effectively closed, large wall crack closed. Winter Track Etch in basement yielded 3.1 pCi/l.
14A	53-67*	61*	0.5-2	1	98	5 vent points, one in each perimeter wall plus second in front wall. One fan in suction. About 0.05 in. WC suction. Top wall voids effectively closed. Winter Track Etch in basement yielded 0.7 pCi/l.
16A	136-327*	240*	2-7	4	98	6 vent points around basement perimeter walls, plus 3 points in perimeter walls around paved, unvented crawl space. One fan in suction. 0.03-0.10 in. WC suction. Top voids covered by caulked sill plate. Flaws in wall/floor joint closed. Levels spike to 15 pCi/l during water usage. Winter Track Etch in basement yielded 2.9 pCi/l.
19	21-51*	35*	3-20	11	68	4 vent points, one in each perimeter wall. One fan in suction. Top wall voids effectively closed in all walls. Smoke tracer testing confirms that all walls are under suction.

(continued)

Table III. continued

House No.	Rn Levels-System Off (pCi/l) Range	Arith. Mean	Rn Levels-System On (pCi/l) Range	Arith. Mean	Percent Reduction In Mean	Comments
Baseboard duct						
1B	126-199*	161*	3-7	5	97	Baseboard ducting around entire perimeter plus both sides of interior load-bearing walls. Two fans blowing into duct. 0.045 in. WC pressure in duct. Extensive closure of wall, slab openings. Fireplace in one wall.
2B	88-503*	238*	2-6	4	98	Baseboard ducting around entire perimeter, plus part of interior wall. Two fans blowing into duct. 0.06 - 0.31 in. WC pressure in duct. Most of top voids covered by caulked sill plate. Fireplace in interior wall. Some brickwork removed to permit closing of top voids in interior wall. Levels spike to 15 pCi/l when clothes washer used.
9A	242-475*	360*	3-10	7	98	Baseboard ducting over French drain around entire perimeter, except in one corner where shower stall covers wall/floor joint. Two fans blowing into duct. Top wall voids generally effectively closed. Fireplace in one wall.
11	**	~ 60*	15-28	21	~ 65	Baseboard ducting over French drain around the 3 exterior walls of row house (common wall not treated). One fan in suction. Suction in ducting 0.2 in. WC near fan, but drops to zero remote from fan, so that part of exterior wall is not being treated. Not all top voids effectively closed. Brick veneer on all exterior walls.

*All measurements were obtained during cold-weather months (November through March) except those marked with an asterisk.
**Insufficient data to determine reliable range.

Table IV. Results with sub-slab suction (pipes through slab), with and without simultaneous block wall ventilation (basement houses with hollow-block foundation walls, with no adjoining slab on grade)

House No.	Sub-slab Suction Only: Mean Rn (pCi/l) System Off	Sub-slab Suction Only: Mean Rn (pCi/l) System On	Sub-slab Suction Only: % Reduction	Sub-slab Plus Wall Suction: Mean Rn (pCi/l) System Off	Sub-slab Plus Wall Suction: Mean Rn (pCi/l) System On	Sub-slab Plus Wall Suction: % Reduction	Comments
3 and 3A	1205* (House 3)	526*	56	1205* (House 3A)	1	99	House 3 has 1 suction point in center of slab (600 ft^2 per suction point), about 0.3 in. WC suction (moderate-suction fan). House 3A supplements sub-slab with 5 wall points, one on each perimeter wall plus second point in rear wall. One fan in suction treats all 6 points, 0.01-0.05 in. WC suction in pipes near entry points. Top wall voids effectively closed. Winter Track Etch in basement of 3A yielded 4.4 pCi/l.
7C and 7D	402 (House 7D)	4	99	402 (House 7C)	26	93	House 7C has 6 sub-slab suction points around perimeter walls, and 1 point near interior load-bearing block wall (160 ft^2 per point); plus 8 dampered wall suction points (6 in perimeter walls, 2 in interior wall, near the corresponding sub-slab points). One fan in suction treats all floor and wall points (0.12-0.15 in. WC suction in sub-slab pipes, 0.02-0.06 in. WC in wall pipes). House 7D has the 7 sub-slab points only, wall pipes dampered to zero flow (0.75-1.0 in. WC suction in sub-slab pipes).
20B and 20C	282* (House 20C)	Not available		282* (House 20B)	4	99	House 20B has 5 sub-slab suction points around three of the perimeter walls in basement (200 ft^2 of basement slab per point), plus 5 dampered wall suction points (one near each sub-slab point), plus suction on interior drain tile under slab of adjoining paved crawl space. One fan treats all points (about 0.2 in. WC suction in sub-slab pipes, probably about 0.02-0.04 in. WC in wall pipes near entry points). Top wall voids covered by caulked sill plate. House 20C has the 5 sub-slab points (and the drain tile) only, wall pipes dampered to zero flow (0.75-1.0 in. WC suction in sub-slab pipes).

*All measurements were obtained during cold-weather months (November through March) except those marked with an asterisk.

Table V. Results with heat recovery ventilators

House No.	HRV Configuration	Basement Results: Mean Rn (pCi/l) HRV Off	Basement Results: Mean Rn (pCi/l) HRV On	Basement Results: % Reduction	Upstairs Results: Mean Rn (pCi/l) HRV Off	Upstairs Results: Mean Rn (pCi/l) HRV On	Upstairs Results: % Reduction	Comments
17A	Stale air removed from basement; all fresh air supplied upstairs	48	58	-19	12	2	81	HRV on high speed. HRV delivering about 180 cfm fresh air upstairs, which would be nominally sufficient to create 1.0 air changes per hour (ach) upstairs, or 0.5 ach for the entire house. The ratio flow in/flow out was roughly 1.4, suggesting a possible slight pressurization. Door between basement and upstairs open.
		48	38	21	12	2	82	As above, but HRV on low speed. HRV delivering about 150 cfm (nominally 0.9 ach upstairs only, or 0.4 ach whole house). Flow ratio 1.0.
	Stale air removed from basement, all fresh air supplied into basement.	73	46	37	19	5	75	HRV on high speed, delivering about 140 cfm of fresh air into basement (nominally 0.8 ach in basement only, 0.4 ach whole house). Door between basement and upstairs open.
		73	46	37	19	7	62	As above, but HRV on low speed. HRV delivering about 110 cfm (nominally 0.6 ach in basement only, or 0.3 ach whole house).

(continued)

Table V. Continued

House No.	HRV Configuration	Basement Results: Mean Rn (pCi/l) HRV Off	Basement Results: Mean Rn (pCi/l) HRV On	Basement Results: % Reduction	Upstairs Results: Mean Rn (pCi/l) HRV Off	Upstairs Results: Mean Rn (pCi/l) HRV On	Upstairs Results: % Reduction	Comments
18A	Stale air removed from basement; all fresh air supplied upstairs.	14	13	6	8	2	74	HRV on high speed, delivering about 175 cfm fresh air upstairs (nominally 1.1 ach first story only, or 0.5 ach whole house). Ratio flow in/flow out was roughly 0.85, suggesting a possible slight depressurization. Door between basement and upstairs was closed.
		14	9	34	8	1.5	81	As above, but HRV on low speed, delivering about 135 cfm (norminally 0.85 ach for first story only, or 0.35 ach whole house). Flow ratio 0.85.
		23	14	38	9	2.5	72	As above, but HRV on high speed again (repeat run one year after first testing). HRV delivering about 145 cfm (nominally 0.95 ach for first story only, or 0.4 ach whole house).
	Stale air removed from basement; all fresh air supplied into basement.	23	13	45	9	4	60	HRV on high speed, delivering about 185 cfm (nominally 1.5 ach for basement only, 0.5 ach whole house).
28A	Stale air removed from basement; all fresh air supplied into basement.	16	9	44	9	7	15	HRV on high speed, delivering about 165 cfm fresh air into basement (nominally 1.3 ach for basement only, or 0.45 ach whole house).

Conversion factors: becquerels per cubic meter = 37 x value in picocuries per liter
liters per second = 0.47 x value in cubic feet per minute